

Study of the $\psi(2S)$ decay to $p\bar{p}\pi^+\pi^-(\pi^0)$

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The branching ratios of $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$ and $\psi(2S) \rightarrow p\bar{p}\omega$, $\omega \rightarrow \pi^+\pi^-\pi^0$ are measured and the $\pi^+\pi^-$ invariant mass distribution in the first decay is discussed by analysing 14 million produced $\psi(2S)$ events collected by the BESII detector at the BEPC.

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In the quarkonium model, the J/ψ and $\psi(2S)$ are respectively the ground state^[1] and the first radial excitation of the 3S $c\bar{c}$ bound state^[2]. As such, their decay is supposed to have a similar feature. In both J/ψ decay and $\psi(2S)$ decay, the $p\bar{p}\omega$ and $p\bar{p}\rho^0$ are allowed three body states. For J/ψ decay, the production of $p\bar{p}\omega$ is observed at the fair fraction^[3] of $(1.30 \pm 0.25) \times 10^{-3}$ relative to other allowed three body states, while only a upper limit is set to the branching ratio^[4] of the production of $p\bar{p}\rho^0$. Therefore, to observe how the $p\bar{p}\omega$ $p\bar{p}\rho^0$ are produced in $\psi(2S)$ decay is very interesting.

The ω decays to $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ at 1.7% and 89.7% branching ratios^[4,5]. The $p\bar{p}\omega$ is observed by BESII^[6]. In the paper, we present the $\pi^+\pi^-$ mass spectrum in $\psi(2S)$ decay to $p\bar{p}\pi^+\pi^-$ and the $\pi^+\pi^-\pi^0$ mass spectrum in $\psi(2S)$ decay to $p\bar{p}\pi^+\pi^-\pi^0$. The analysis is based on 14 million produced $\psi(2S)$ events collected by the BESII detector at the BEPC.

This study shows an unknown bump of about 20 MeV width at 727 MeV in $\pi^+\pi^-$ mass spectra. The BES apparatus is a magnetic spectrometer working at e^+e^- colliding mode, which has been fully described elsewhere^[7].

The decay of $\psi(2S)$ to $p\bar{p}\pi^+\pi^-\pi^0$ is discussed first because of ω decays to $\pi^+\pi^-\pi^0$ in large branching ratio.

Candidates for $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-\pi^0$ events are selected by requiring exactly four reconstructed charged tracks in the drift chamber with zero net charge. Tracks with transverse momentum $p_{xy} > 0.08$ GeV and $|\cos\theta_{ch}| < 0.85$ are accepted, where θ_{ch} is the polar angle with respect to the beam direction. The particles are identified by requiring that their combination weights of time-of-flight (TOF) and the ionization energy loss (dE/dx) in the drift chamber be consistent with the corresponding particle hypothesis. The events with at least two charged particle satisfying proton and anti-proton hypotheses and one satisfying pion hypothesis are selected.

To remove the contamination from $\psi(2S) \rightarrow \Lambda\bar{\Lambda}\pi^0$, $M_{p\pi^-} > 1.15$ GeV and $M_{\bar{p}\pi^+} > 1.15$ GeV are required.

An isolated photon is defined as a cluster in the barrel shower counter with at least two readout layers hit, energy larger than 30 MeV, outside a 25° cone around the \bar{p} and outside a 12° cone around other charged particles to reject possible fake photons produced by \bar{p} annihilation and/or radiated by other charged particles inside the shower counter. The cluster is also required to have its incident direction (from the interaction point to the first hit point in BSC) inside a 20° cone around the cluster developing direction.

The events are kinematically fitted for the $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-\pi^0$ topology by imposing energy and momentum constraints (4C). $\chi^2_{p\bar{p}\pi^+\pi^-\gamma\gamma} < 20$ and $\chi^2_{p\bar{p}\pi^+\pi^-\gamma\gamma} < \chi^2_{p\bar{p}\pi^+\pi^-\gamma}$ to remove $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-\gamma$.

The combination with the smallest χ^2 in the 4C fit is chosen to identify the radiative photon if there are more than two photon candidates in an event. Fig. 1 shows the $\gamma\gamma$ invariant mass distribution. The π^0 signal is seen at 0.135 GeV. To select π^0 , it is required $|M_{\gamma\gamma} - 0.135| < 0.040$ GeV (3σ).

A contamination is $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow p\bar{p}\pi^0$. To remove it it is required $|M_{p\bar{p}\pi^0} - 3.097| > 0.065$ GeV (3σ). (why do not use $M_{p\bar{p}\pi^0} < 3.0$ GeV, because $M_{p\bar{p}\pi^0}$ distribution is around 3.0 GeV for $\psi(2S) \rightarrow p\bar{p}\omega$, $\omega \rightarrow \pi^+\pi^-\pi^0$.)

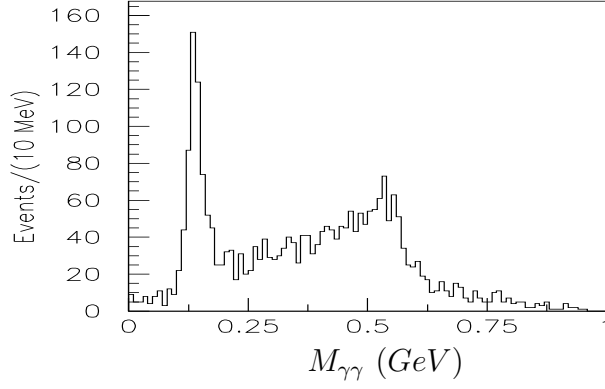


Fig. 1. $\gamma\gamma$ invariant mass for $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-\gamma\gamma$.

550 events are obtained for $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-\pi^0$. $\pi^+\pi^-\pi^0$ invariant mass is shown in Fig. 2. At 0.783 GeV is ω signal. The mass resolution and efficiency though Monte Carlo simulation are obtained to be 14.6 MeV and 3.6%.

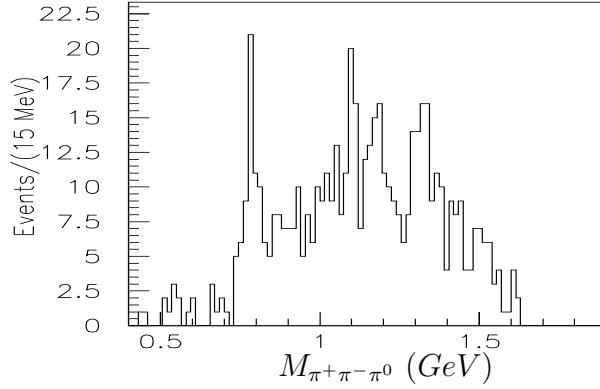


Fig. 2 $\pi^+\pi^-\pi^0$ invariant mass for $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-\pi^0$.

The ω mass, width, event number can be obtained using unbinned Breit-wigner fit. The background is fitted with 4th order nomial. $M_\omega = 783.4 \pm 4.5 \pm 0.2 \text{ MeV}$. $\Gamma_\omega = 12.7 \pm 7.1 \pm 3.0 \text{ MeV}$. $N_{events} = 35.0 \pm 6.0 \pm 6.7$.

There are not contriburion to ω signal from continuum data, which id derived from $6.42(1 \pm 4\%)pb^{-1}$ data at 3.65 GeV.

The branching ratio is $Br(\psi(2S) \rightarrow p\bar{p}\omega, \omega \rightarrow \pi^+\pi^-\pi^0) = \frac{N_{measured}}{\epsilon N_{\psi(2S)}} = (6.9 \pm 1.2 \pm 1.3) \times 10^{-5}$.

$$Br(\psi(2S) \rightarrow p\bar{p}\omega) = (7.7 \pm 1.3 \pm 1.4) \times 10^{-5}.$$

The BES I data gives^[6] $Br(\psi(2S) \rightarrow p\bar{p}\omega) = (8.0 \pm 3.0 \pm 1.0) \times 10^{-5}$.

Now the decay of $\psi(2S)$ to $p\bar{p}\pi^+\pi^-$ is discussed. The charged particle are selected as above. To remove the one or multiple photon events, the missing momentum is required to be $p_{missing} < 0.1 \text{ GeV}$. $\psi(2S) \rightarrow \Lambda\bar{\Lambda}$ is a contamination source. It is removed by $M_{p\pi^+} > 1.15 \text{ GeV}$ and $M_{\bar{p}\pi^-} > 1.15 \text{ GeV}$.

Another contamination source is $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow p\bar{p}$. It is removed by requiring $M_{p\bar{p}} < 3.0 \text{ GeV}$. The $p\bar{p}\pi^+\pi^-$ mass is shown in Fig. 3. It is $\psi(2S)$ signal. Its resolution is 36 MeV. $|M_{p\bar{p}\pi^+\pi^-} - 3.686| < 0.1 \text{ GeV}$ is required.

To remove $\psi(2S) \rightarrow p\bar{p}K^+K^-$ 4c fit is performed. $\chi^2_{\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-} < 30$ and $\chi^2_{\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-} < \chi^2_{\psi(2S) \rightarrow p\bar{p}K^+K^-}$ is required.

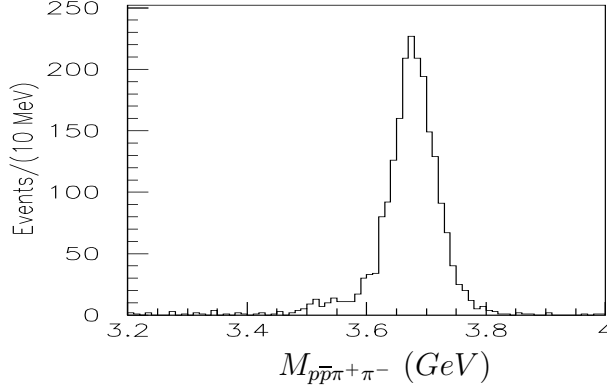


Fig. 3. $p\bar{p}\pi^+\pi^-$ invariant mass distribution for $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$ candidates.

The $\pi^+\pi^-$ invariant mass distribution is shown in Fig. 4. 1691 events are there. Two narrow bumps can be seen at 727.0 and 783.0 MeV and a little bump at 977.0 GeV, i.e. the position of $f_0(980)$. From Monte Carlo simulation, the BES-II detector acceptance efficiencies and the mass resolutions at three points are obtained. The mass resolutions are 6.0 MeV at the first two points and 6.8 MeV at 977.0 GeV. The efficiencies are 21.4%, 21.8% and 22.4%.

Their masses, widths, event numbers and statistic significance (S.S.) can be obtained using unbinned Breit-wigner fit. The background is fitted with 3th order nomial. Each of the first two bumps is described using free parameters: area, width, mass and one fixed parameter: resolution. The mass and width of $f_0(980)$ are fixed at the values of PDG2004 977.0 MeV and 44.0 MeV. The mass resolution of $f_0(980)$ is fixed.

The table 1 shows these values

Table 1. The parameters of bumps by fitting the first two as unkown ones.

	mass (MeV)	width (MeV)	Event	S.S. (σ)
bump1	$726.9 \pm 4.1 \pm 2.1$	$20.7 \pm 12.5 \pm 8.1$	$69.0 \pm 15.8 \pm 12.8$	4.9
bump2	$783.0 \pm 2.2 \pm 0.4$	$3.2 \pm 5.6 \pm 1.2$	$42.5 \pm 10.6 \pm 10.7$	5.0
$f_0(980)$	977.0	44.0	$8.8 \pm 16.4^{+5.6}_{-8.8}$	0.5

statistic significance is defined as $significance = \sqrt{2 \times (\ln L_{max} - \ln L_0)}$ Where L_{max} is likelihood function value for 1. the first two signals yield with resolutions fixed and areas, masses and widths to float, 2. the $f_0(980)$ signal yield with resolution, mass, width fixed and area to float and 3. the background shape parameters to float. L_0 is the likelihood function value for the signal hypothesis under consideration corresponding to a zero yield and the other two signals yield as in L_{max} .

The mass and width of bump2 are consistent with those of ω . Bump1 is unknown. The known particles listed in PDG2004^[4] have no consistent masses and widths with those of bump1.

The branching ratios are

$$Br(\psi(2S) \rightarrow p\bar{p}bump1, bump1 \rightarrow \pi^+\pi^-) =$$

$$\frac{N_{measured}}{\epsilon N_{\psi(2S)}} = (2.3 \pm 0.5 \pm 0.4) \times 10^{-5},$$

$$\begin{aligned} Br(\psi(2S) \rightarrow p\bar{p}bump2, bump2 \rightarrow \pi^+\pi^-) \\ = (1.4 \pm 0.4 \pm 0.4) \times 10^{-5}, \end{aligned}$$

$$Br(\psi(2S) \rightarrow p\bar{p}f_0(980), f_0(980) \rightarrow \pi^+\pi^-)$$

$$= (2.8 \pm 5.2_{-2.8}^{+1.8}) \times 10^{-6},$$

From $Br(\psi(2S) \rightarrow p\bar{p}\omega, \omega \rightarrow \pi^+\pi^-\pi^0)$, it is derived $Br(\psi(2S) \rightarrow p\bar{p}\omega, \omega \rightarrow \pi^+\pi^-) = (1.3 \pm 0.2 \pm 0.2) \times 10^{-6}$, which is not consistent with branching ratio of bump2 production.

$$Br(\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-) = \frac{(1691 - 123 - 27) \pm 40.0 \pm 175.6}{0.22 \times 14 \times 10^6} = (5.0 \pm 0.1 \pm 0.6) \times 10^{-4},$$

where $\Lambda\bar{\Lambda}$ is excluded, 123 is contribution of continuum data, which is derived from $6.42(1 \pm 4\%)pb^{-1}$ data at 3.65 GeV. 27 is from sidebands. 40.0 is statistical error. 175.6 is systematic error. The efficiency is 22.0%. The sideband events are obtained using the cut $0.1 < |M_{p\bar{p}\pi^+\pi^-} - 3.686| < 0.2$ GeV and the same other cuts for Fig. 4.

In addition to $\Lambda\bar{\Lambda}$, two decay processes of $\psi(2S)$ have $p\bar{p}\pi^+\pi^-$ final state. One is $\psi(2S) \rightarrow \Delta^{++}\Delta^{--}$ with the branching ratio of $(1.28 \pm 0.35) \times 10^{-4}$ given by BES^[4,8]. Another is direct decay $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$. The branching ratio given by PDG2004^[4,9] is $Br(\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-) = (8.0 \pm 2.0) \times 10^{-4}$, which includes the contribution from the $\Lambda\bar{\Lambda}$, $\Delta^{++}\Delta^{--}$ and direct decay.

Then what is branching ratio of direct decay $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$ from this measurement? Using $Br(\psi(2S) \rightarrow \Delta^{++}\Delta^{--})$, Monte Carlo simulation shows that 368 $\Delta^{++}\Delta^{--}$ events contribute Fig. 4, i.e. number of direct decay $p\bar{p}\pi^+\pi^-$ is $1691 - 123 - 27 - 368 - 65.9 - 42.5 = 1064.6$, two bumps are excluded (because number of $f_0(980)$ is small and has large statistics, it is ignored). The corresponding branching ratio is 3.5×10^{-4} . In Fig. 4 the solid line is from Monte Carlo events of $\psi(2S) \rightarrow \Delta^{++}\Delta^{--}$ with branching ratio of 1.28×10^{-4} plus direct decay $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$ with branching ratio of 3.5×10^{-4} .

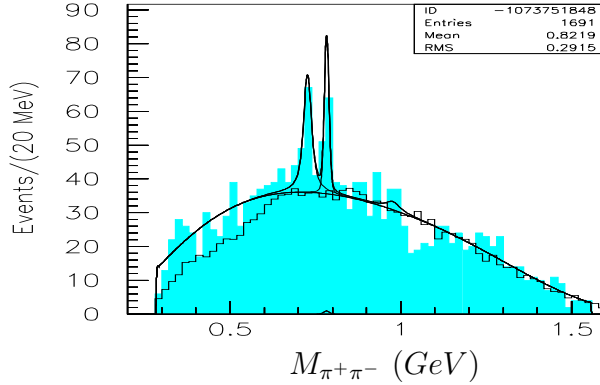


Fig. 4. $\pi^+\pi^-$ invariant mass distribution for $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$. The shaded area is data. The smooth line is from BW fit. The solid line is from Monte Carlo simulation $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$ and $\psi(2S) \rightarrow \Delta^{++}\Delta^{--}$. The small peak at 0.782 GeV near bottom line is from Monte Carlo simulation with $Br(\psi(2S) \rightarrow p\bar{p}\omega, \omega \rightarrow \pi^+\pi^-) = 1.3 \times 10^{-6}$.

The sample of 14×10^6 Monte Carlo inclusive $\psi(2S)$ decay from lund-charm generator^[10] is used to estimate the background. The sample is through the same cuts. 4686 events are selected. Among the events, the contamination is shown in table 2. Monte Carlo simulation for each channel shows these channels maybe have no contributions to $p\bar{p}\pi^+\pi^-$ invariant mass distribution around 0.727 and 0.783 GeV.

Table 2. Contamination from $\psi(2S)$ decay to anything

source	number	bran. ratio
$\eta' p\bar{p}, \eta' \rightarrow \gamma \rho$	22	
$\eta p\bar{p}, \eta \rightarrow \gamma \pi^+ \pi^-$	13	
$\chi_{c1} \gamma, \chi_{c1} \rightarrow p\bar{p} \rho$	1	$< 4.5 \times 10^{-5*}$
$\chi_{c2} \gamma, \chi_{c2} \rightarrow p\bar{p} \rho$	5	$< 9.5 \times 10^{-5*}$
$\chi_{c2} \gamma, \chi_{c2} \rightarrow a1(1260)^0 \pi^0$	1	
$\chi_{c2} \gamma, \chi_{c2} \rightarrow p\bar{p} \pi^+ \pi^-$	1	9.5×10^{-5}
$\pi^0 \pi^+ \bar{p} \Delta^{--}$	1	
$p\bar{p} \pi^0$	1	1.4×10^{-4}
$p\bar{p} \gamma$	2	
$\pi + \pi^+ J/\psi, J/\psi \rightarrow e^+ e^-$	1	$< 1.8 \times 10^{-2}$
sum	48	

here, branching ratios come from PDG2004. $*Br(\chi_{c1} \gamma, \chi_{c1} \rightarrow p\bar{p} \rho) < Br(\chi_{c1} \gamma, \chi_{c1} \rightarrow p\bar{p} \pi^+ \pi^-) = 4.5 \times 10^{-5}$. $Br(\chi_{c2} \gamma, \chi_{c2} \rightarrow p\bar{p} \rho) < Br(\chi_{c2} \gamma, \chi_{c2} \rightarrow p\bar{p} \pi^+ \pi^-) = 9.5 \times 10^{-5}$.

Systematic errors for efficiency are caused by difference between data and MC simulation. Studies have determined these errors to be 8% for the tracking efficiency, 2% for photon identification, ^[10], 5.6% for PID, 1.9%, 11.1%, 16.3%, -78.6%, 8.4% for kinematic fit of $p\bar{p} \pi^+ \pi^-$, $p\bar{p} \text{bump1}$, $p\bar{p} \text{bump2}$, $p\bar{p} f_0(980)$ and $p\bar{p} \omega$, 0%, 0.01%, 4.1%, 62.5% and 1.2% for BW fit of $p\bar{p} \pi^+ \pi^-$, $p\bar{p} \text{bump1}$, $p\bar{p} \text{bump2}$, $p\bar{p} f_0(980)$ using 4th order nomial to describe the background and $p\bar{p} \omega$ using 5th order nomial to decribe the background, 1.1%, 1.7%, 8.5%, -12.9% and 5.9% for $|\cos\theta| < 0.8$ for $p\bar{p} \pi^+ \pi^-$, $p\bar{p} \text{bump1}$, $p\bar{p} \text{bump2}$, $p\bar{p} f_0(980)$ and $p\bar{p} \omega$, 0.5%, 0.5% and 3.1% for efficiencies of bump1, bump2 and f_0 , 0.6%, 9.7%, 10.5% and -100.0% for p_{missing} for $p\bar{p} \pi^+ \pi^-$, $p\bar{p} \text{bump1}$, $p\bar{p} \text{bump2}$ and $p\bar{p} f_0(980)$, 5.0% for number of $\psi(2S)$ events. Total systematic errors are 11.2%, 18.5%, 25.2%, $^{+63.4}_{-100}$ and 15.4% for $p\bar{p} \pi^+ \pi^-$, bump1, bump2, $f_0(980)$ and ω respectively.

The parameters of the two bumps in Fig. 4 are obtained by fitting them as completely unknown partilces. But theoretically $\psi(2S)$ can decay to $p\bar{p} \rho^0$ ($J^{PC} = 1^{--}$) and $p\bar{p} \omega$ (1^{--}). This gives rise to the questions: 1.the ρ^0 and ω plus their interference can fit? 2. the ω plus one unknown bump1 can fit? 3. the ρ^0 and ω and their interference plus one unknown bump1 can fit the two bumps?

Fig. 5 showes Breit-Winger fits for these three combinations, in which the the masses and widthes of the ρ^0 , ω and $f_0(980)$ are fixed at PDG2004. The fitting parameters are given in table 3.

Table 3. Breit-Winger fitting parameters

combination	bump	mass (MeV)	width (MeV)	event	S.S.	Br.(10^{-5})
1	ρ^0	776.0	149.0	$156.6 \pm 31.9 \pm 36.8$	5.1	$5.4 \pm 1.1 \pm 1.3$
	ω	782.5	8.5	$13.0 \pm 7.7 \pm 5.1$	1.8	$0.43 \pm 0.25 \pm 0.17$
	$f_0(980)$	977.0	44.0	$20.8 \pm 16.0 \pm 9.4$	1.3	$0.66 \pm 0.52 \pm 0.30$
2	ω			$49.9 \pm 12.2 \pm 10.1$	5.0	$1.6 \pm 0.4 \pm 0.3$
	$f_0(980)$			$9.5 \pm 16.4^{+6.0}_{-9.5}$	0.6	$0.30 \pm 0.52^{+0.19}_{-0.30}$
	bump1	$726.7 \pm 4.0 \pm 2.5$	$19.4 \pm 10.8 \pm 7.0$	$66.5 \pm 15.6 \pm 14.9$	4.9	$2.2 \pm 0.5 \pm 0.5$
3	ρ^0			$18.5 \pm 13.2 \pm 11.2$	4.5	$6.4 \pm 4.6 \pm 3.9$
	ω			$35.8 \pm 15.8 \pm 6.2$	3.8	$1.2 \pm 0.5 \pm 0.2$
	$f_0(980)$			$20.1 \pm 15.6 \pm 9.7$	1.0	$0.64 \pm 0.50 \pm 0.31$
	bump1	$726.8 \pm 4.2 \pm 2.3$	$18.4 \pm 12.5 \pm 7.2$	$63.7 \pm 14.4 \pm 11.4$	4.0	$2.1 \pm 0.5 \pm 0.4$

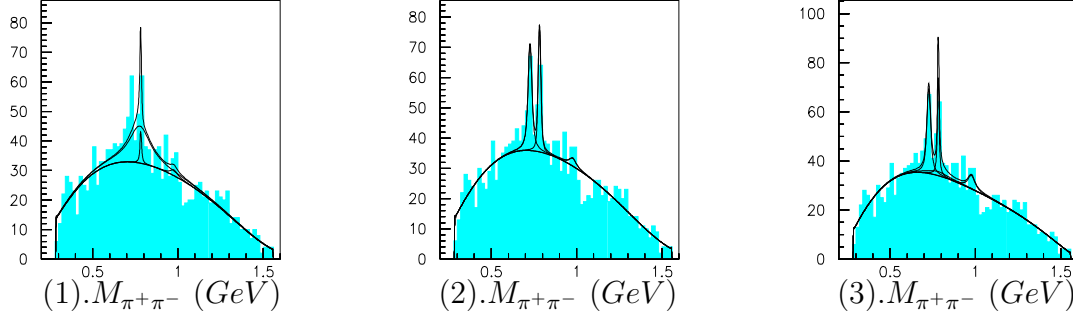


Fig. 5 Three kind of combinations of $\rho^0 \omega f_0(980)$ and bump1 to fit the $\pi^+\pi^-$ invariant mass distribution from $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$. (1) $\rho^0 + \omega + \rho^0\omega$ interference + $f_0(980)$. (2) unknown bump1 + $\omega + f_0(980)$. (3) unknown bump1 + $\rho^0 + \omega + \rho\omega$ interference + $f_0(980)$.

In this work, $br(\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-) = (5.0 \pm 0.1 \pm 0.6) \times 10^{-4}$ and $br(\psi(2S) \rightarrow p\bar{p}\omega) = (7.7 \pm 1.3 \pm 1.4) \times 10^{-5}$ are measured by analysis of BES-II 14 million $\psi(2S)$ events sample. This leads to the observation of two bumps in $\pi^+\pi^-$ mass spectrum in the decay process $\psi(2S) \rightarrow p\bar{p}\pi^+\pi^-$. The bumps are not observed in $J/\psi \rightarrow p\bar{p}\pi^+\pi^-$ ^[4]. The mass and width of the first bump can not match those of any particles in PDG2004. Another bump has a consistent mass and width with those of ω . But if bump2 is real ω , there is no consistency between the branching ratio for $\psi(2S) \rightarrow p\bar{p}bump2, bump2 \rightarrow \pi^+\pi^-$ and the branching ratio for $\psi(2S) \rightarrow p\bar{p}\omega, \omega \rightarrow \pi^+\pi^0$.

Duo to small statistics, the quantum number J^{PC} is not set for bump1 and bump2. The bump1 has a statistical significance $4.0 < S.S. < 4.9 \sigma$. Whether the two bumps come from statistical fluctuation should be confirmed by larger statistics of $\psi(2S)$ events.

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